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Effects of damming and climatic change on the eco-hydrological system: A case study in the Yalong River, southwest China

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ABSTRACT

The eco-hydrological system in China is undergoing dramatic changes in recent decades due to climate change and construction of cascade dams for power production. Given that multiple drivers often interact in complex and nonadditive ways, the purpose of this study is to predict future changes in runoff and fish habitat quality of the Yalong River basin attributed to the individual and combined effects of cascade dam construction and climate change. The bias corrected and spatially downscaled CMIP5 GCM projections are used to drive the Soil and Water Assessment Tool hydrological model and to simulate and predict runoff responses under diverse scenarios. The physical habitat simulation model is established to describe the relationship between river hydrology and fish habitat quality and to assess the individual and combined effects of cascade dam construction and climate change. The mean annual temperature and precipitation of the Yalong River in 2020–2100 are predicted to increase at a rate of 0.016–0.487 °C/10a and 4.55–10.13 mm/10a, with an increase of 1.63–3.25 °C and 0.66–3.34% in comparison with those in 1957–2012, respectively. While, the mean annual runoff of the middle and lower reaches is increased by 11.77%–16.63% and 14.02%–19.02% compared with that in the history, respectively. The construction of cascade dams could significantly improve the fish habitat quality of the Yalong River basin, especially in dry seasons, and consequently the ecological conservation degree is increased by about 2%. In the middle reaches, changes in runoff from February to October are mainly determined by cascade dam construction, but the effect of climate change becomes more pronounced from November to January. Similarly, cascade dam construction has a more significant effect on runoff of the lower reaches than climate change except in November and December.

1. Introduction

Considerable concerns have been raised about the construction of cascade dams and regional climate change in southwest China, as the water resources there account for more than 75% of the hydropower resources in China (Chen et al., 2017). The Yalong River is a major tributary of the Yangtze River flowing between the Shaluli Mountains to the west and the Daxue Mountains to the east in southwest China (He et al., 2015), and it has been extensively developed in recent years for hydropower production to meet the increasing demand for energy. In this century, a total of 23 cascade dams will have been constructed for the mainstream of the Yalong River, one of China's 13 major hydropower bases, which could dramatically alter the flow regime and ecosystem of the river. What makes it even worse is that, as the river is located in the transition zone of East Asian, Indian and Tibetan Plateau monsoons, climate change induced by global warming may also have an impact on its eco-hydrological system (Palmer et al., 2009). The largest positive trend for runoff variability (0.41%/year) is observed in southwest China (Leng et al., 2015). Thus, there is a need to evaluate individual and combined effects of climate change and cascade dam construction on the eco-hydrological system of the Yalong River basin (Zhao et al., 2013).

The damming effect on runoff and ecological alteration has been a topic of considerable research interest (Ding et al., 2018; Wen et al., 2018). For instance, the discharge of the Lancang-Mekong River, the largest river in southwest China, in dry season is obviously lower in the post-dam period than in the pre-dam period, whereas that in wet season is marginally lower in the post-dam period (Räsänen et al., 2017; Tang

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et al., 2014). In terms of ecological alteration, fish habitat quality is sensitive to flow regulation. In southwest China, the construction of cascade dams is recognized as a major threat to fish habitat quality due to its significant impact on the continuity, flow distribution, organic matter, flow velocity, water depth and temperature (Fan et al., 2015; Li et al., 2013; Li et al., 2011b; Yi et al., 2014; Zhuang et al., 1997). However, Zhai et al. (2010) also argued that the ecosystem integrity of the river could be improved after river regulation. In addition, it is important to note that most previous studies have focused on a single dam, but the fact is that cascade dams are very likely to have a more complex and substantial effect than a single dam.

Climate change can also have a substantial impact on regional hydrological cycles and subsequent changes in river flow regime (Guo et al., 2018; Tang et al., 2015; Wen et al., 2015). Hydrological regime is closely related to climate, and thus change in hydrological regime can be regarded as a particularly valuable indicator of climate change (Archer and Fowler, 2008; Naik and Jay, 2011; Singh et al., 2010). Furthermore, precipitation shows a more apparent increasing trend in the tributary, the Yalong River, than in the mainstream, the Jinsha River (Liu and Sun, 2013). The drying trend is also likely to be aggravated as a consequence of more intense climate extremes (Ma and Zhou, 2015; Wen et al., 2016a; Zhai et al., 2010). Against this background, considerable research has been conducted on changes in aquatic ecology in response to climate change. It is reported that climate change has an effect on sediment trapping, water conservation and species conservation in southwest China, resulting in slight degradation of the ecological and environmental quality in recent decades (Guo et al., 2016; Wen et al., 2016b). Jiang and Zhang (2016) proposed the InVEST model to assess habitat quality in southwest China. However, future changes in fish habitat quantity of the Yalong River remain to be elucidated. Another issue associated with the impact of future climate change is the General Circulation Model (GCM) projections. The GCM outputs tend to be biased wet, dry, cool and/or warm in comparison with observations, and thus the reliability and accuracy might be undermined.

Despite the recognition of the complex and nonadditive interaction between climate change and cascade dam construction, their effects on ecohydrology in southwest China are typically studied independently. The purpose of this study is to predict future changes in streamflow and fish habitat quality of the Yalong River attributed to the individual and combined impacts of cascade reservoirs and climate change. The bias corrected and spatially downscaled CMIP5 GCM projections were used to drive the Soil and Water Assessment Tool (SWAT) hydrological model and to simulate and predict runoff responses under different scenarios. The relationship between river hydrology and fish habitat quality was obtained through a fish habitat model (Chen et al., 2013; Li et al., 2011a). Finally, the relative change rate was used to assess individual and combined impacts of cascade dams and climate change.

2. Research area and data

2.1. Research area

2.1.1. Yalong River basin

The Yalong River is the largest tributary of the Jinsha River in the southern Tibetan Plateau (25°12–34°9N, 96°47–102°42E), and it runs from the northwest to the southeast with a total basin area of approximately 136,000 km^2 and a mainstream length of 1571 km, as shown in Fig. 1.

Hydro-climatological condition in southwestern China is quite typical and vital for our research. Located in the subtropical monsoon climate zone, as well as spanning more than seven latitudes, the average temperature of the basin is −4.9 °C ~ 19.7 °C, decreasing from south to north, and with increasing altitude. The average annual rainfall of the basin is 500–2470 mm, indicating an overall decreasing trend from northwest to southeast over the entire basin. In addition, the wet and dry seasons are quite evident here, the flood season (June to October) accounts for around 77% of the total annual runoff, recharged mainly by precipitation, while the runoff is in the dry season (from November to next May) is supplied by melting snow and groundwater.

2.1.2. Cascade reservoirs

Of the 23 cascade hydropower stations officially approved on the mainstream of Yalong River, 11 reservoirs located upstream the Lianghekou Reservoir are currently in the planning stage; while 12 reservoirs located downstream the Lianghekou Reservoir from Lianghekou to Hekou are in the designing stage or under construction, or have been constructed. That is, the regulation capacity of runoff is mainly concentrated in the middle and lower reaches of the Yalong River. Of these 12 reservoirs, three reservoirs (Lianghekou, JinpingI and Er'tan) have high regulation capacity, and the rest eight reservoirs are daily-regulated run-of-river hydropower stations which will cause no significant changes in flow regime on a 10-day basis (the time step used in this study) and thus not considered in this study. In addition, Ertan Reservoir (seasonal regulation) located at the downstream of the catchment section of interest in this study is also not considered. Therefore, we mainly focus on the impact of Lianghekou Reservoir and JinpingI Reservoir, and their key parameters and locations are shown in Table 1 and Fig. 1.

2.2. Research data

2.2.1. Observed and GCM projected climate data

The historical climate data (daily precipitation, maximum and minimum air temperature) for the period 1957–2012 were obtained from China Metrological Data Sharing Service and used to calibrate the hydrological model of the Yalong River basin and to downscale GCM outputs to a finer resolution. Six meteorological stations are selected in this study, including Qingshuihe (ID No. 56034), Shiqu (ID No. 56038), Ganzi (ID No. 56146), Xinlong (ID No. 56251), Daofu (ID No. 56167) and Litang (ID No. 56257), as shown in Fig. 1. For climate projections, BCC-CSM1-1 was used due to its good performance in climate simulation in southwest China. We analyzed daily precipitation and maximum and minimum near-surface air temperatures for the period 2020–2100, which could be obtained from http://cmip-pcmdi.llnl.gov/. Three Representative Concentration Pathways (RCP) scenarios are selected in this study, including RCP2.6, RCP4.5 and RCP8.5, which are defined according to their total radiative forcing in 2100 relative to pre-industrial values (+2.6, +4.5 and +8.5 W/m^2, respectively) and used to represent low, medium and high emission conditions.

2.2.2. Runoff and fish habitat data

The runoff data are collected at the Ya River and Jinping stations (Fig. 1) on a daily basis from January 1957 to December 2012; while the behavior data of target fish species *Schizothorax chongi* (*S. chongi*) are collected by Li et al. (2011a).

2.2.3. Geospatial data

In order to simulate the hydrological process using the SWAT model, some other data are required, including Digital Elevation Model (DEM), land use/cover data and soil map. The NASA Shuttle Radar Topography Mission (SRTM) DEM (90 m) was used to generate the boundary and stream network of the basin. The soil type and land use data were extracted from the Harmonized World Soil Database V1.2 (30 arc-second resolution) provided by the Food and Agriculture Organization of the United Nations (FAO), and then reclassified according to the requirement of the SWAT model and the China Soil Classification System.

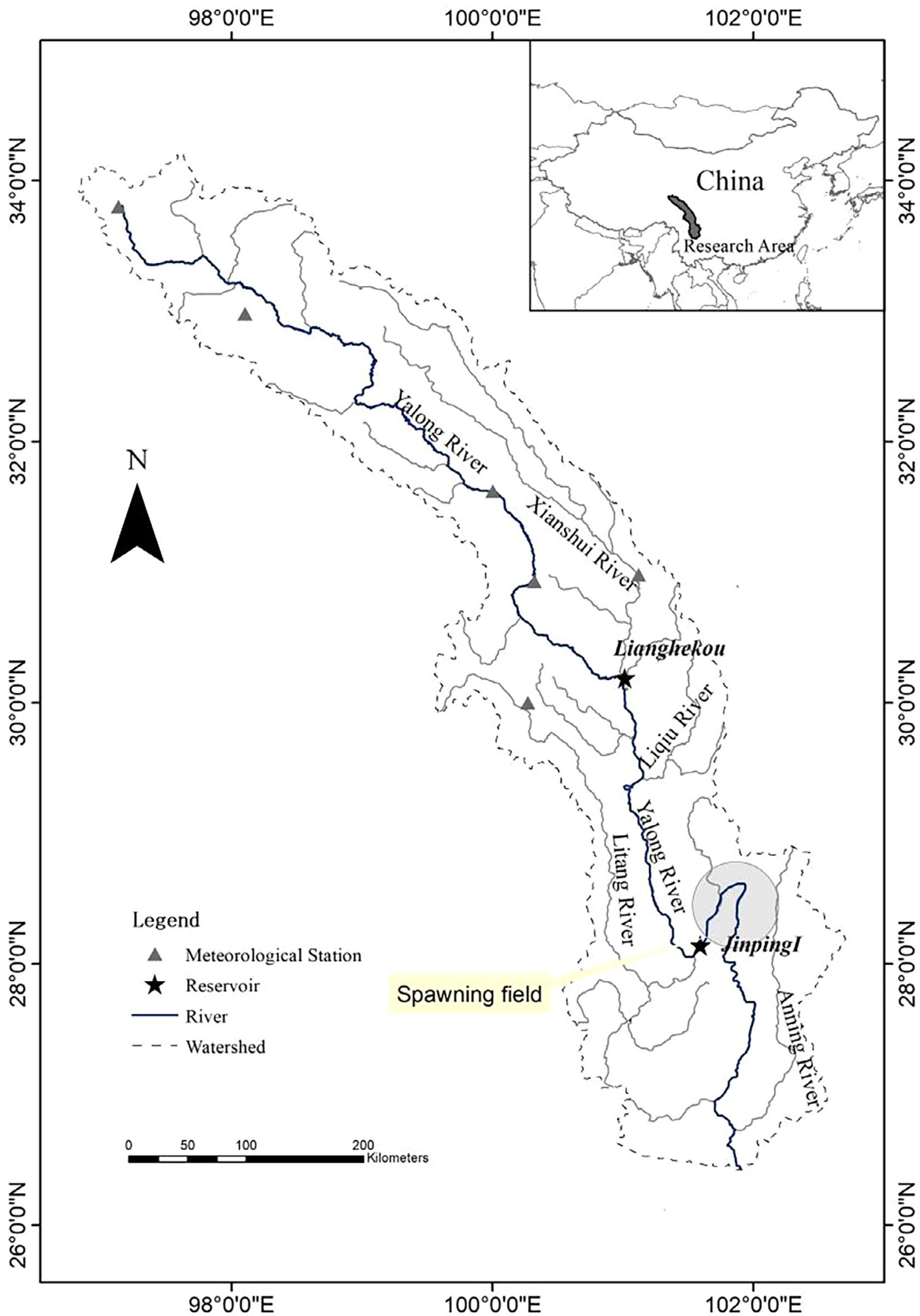

Fig. 1. Location, river network and cascaded reservoirs of the Yalong River.

3. Methods

3.1. Bias correction and spatial disaggregation

The comparison of historical simulation results from GCMs with observations often shows that the simulations tend to be biased wet, dry, cool, and/or warm, and the bias varies with location, season and variable. To address this problem, Bias Correction and Spatial Disaggregation (BCSD) method, a statistical downscaling technique developed by Wood et al. (2002), is performed to establish empirical relationships between GCM-resolution climate variables and local climate and to reproduce regional climate features. It offers a more immediate solution and significantly lower computing requirements, and could be easily transferred to other regions.

The classical BCSD method is proposed for monthly temperature and precipitation downscaling. However, this method could also be

Table 1
Properties of Lianghekou Reservoir and JinpingI Reservoir on the Yalong River.

Properties	Unit	Lianghekou Reservoir	JinpingI Reservoir
Basin area	km^2	65,725	102,560
Regulation ability	–	Multi-year regulation	Annual regulation
Mean annual flow	m^3/s	663	1200
Available storage	10^8m^3	65.6	49.1
Normal water level	m	2865	1880
Dead water level	m	2785	1800
Maximum turbine release	m^3/s	1492	2024
Output efficiency	–	8.6	8.6

performed on a daily time step. Generally, it mainly involves the following two steps: (1) Bias Correction. A quantile mapping of daily temperature and precipitation from GCMs to observations regridded to the coarse model resolution is employed to identify and remove the bias. Specifically, a bias-corrected value for a GCM-simulated daily value is retrieved by using the CDF for the GCM to determine the quantile associated with the value, and then drawing the observed value from that same day's CDF for the same quantile. Bias correction matches the statistical moments of observations and GCM output covering a common time period (e.g. 20th century), and accordingly adjusts for biases in GCM output for projected time periods (e.g. 21st century). (2) Spatial Disaggregation. The bias-corrected precipitation and temperature are spatially disaggregated to the fine-resolution grid by SYMAP interpolating and then applying fine-resolution spatial anomaly patterns derived from the observations. The anomalies are calculated as the correction factors (for precipitation) and summands (for temperature) between the fine-resolution observations and the coarsened observations interpolated to the fine-resolution grid (Wood et al., 2004).

The gaged-based observations are converted to the grid-based data and are used as the historical records to remove the bias in CMIP5 GCM projections. All future precipitation and temperature projections are downscaled to the grid scale (0.5° × 0.5°) on a daily basis.

3.2. SWAT hydrological simulation

As a river basin-scale model, SWAT has got growing adoption in solving hydrological and/or environmental issues (Gassman et al., 2014). In the current work, the catchment is divided into several subbasins and each subbasin is further divided into a number of Hydrological Response Units (HRUs) with homogeneous soil type and land use. Each HRU operates in five phases: (1) precipitation interception, (2) surface runoff, (3) soil and root zone infiltration, (4) evapotranspiration and soil and snow evaporation, and (5) groundwater flow. The detailed procedure is described in Arnold et al. (1998). Meanwhile, SWAT-CUP (Calibration and Uncertainty Procedures) (Abbaspour, 2014) is used to calibrate SWAT.

The performance of the model is evaluated by Nash-Sutcliffe Efficiency (*NSE*) and coefficient of determination (R2), defined as Eqs. (1) and (2), respectively(Krause et al., 2005). The simulation is considered to be acceptable if $NSE > 0.5$ mean or $R^2 > 0.5$.

$$NSE = 1 - \frac{\sum_{i=1}^{n} (Q_{o,i} - Q_{m,i})^2}{\sum_{i=1}^{n} (Q_{o,i} - \bar{\bar{Q}}_o)^2} \tag{1}$$

$$R^2 = \frac{[\sum_{i=1}^{n} (Q_{o,i} - \bar{Q}_o)(Q_{s,i} - \bar{Q}_s)]^2}{\sum_{i=1}^{n} (Q_{o,i} - \bar{Q}_o)^2 \sum_{i=1}^{n} (Q_{s,i} - \bar{Q}_s)^2} \tag{2}$$

where $Q_{o,i}$ and $Q_{m,i}$ are the i^{th} observed and simulated data; $\bar{Q}_o$ and $\bar{Q}_s$ are the mean observed and simulated data; and n is the total number of observations, respectively.

3.3. Habitat simulation model

In order to simulate the relationship between streamflow and fish habitat quality for different life stages of *S. chongi*, the fish habitat model coupled with the water environment model Li et al. (2011a) was used to determine the optimal ecological flow for a given river reach. The governing equations of the water environment model, whose results will be applied for the fish habitat model, are as follows:

$$\frac{\partial H}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = Q_a \tag{3}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + fv + v\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \frac{1}{\rho_0 H}\tau_x \tag{4}$$

$$\frac{\partial y}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} - fu + v\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{1}{\rho_0 H}\tau_y \tag{5}$$

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} = D_x\frac{\partial^2 c}{\partial x^2} + D_y\frac{\partial^2 c}{\partial y^2} + S + f_R(c, t) \tag{6}$$

where Q_a is the discharge or withdrawal, m^3/s; H is the water level, m; u and v are the velocities in the x and y direction, m/s; v is the horizontal eddy viscosity coefficient, m^2/s; f is the Coriolis parameter; τ_x and τ_y are the bottom shear stresses, N/m; c is the concentration, kg/m^3; D_x and D_y are the disperse coefficients, m^2/s; S is the source or sink term, and $f_R(c, t)$ is the reaction term, respectively.

The river section and aquatic species most vulnerable to changes in stream flow should be identified for habitat modeling (Maddock et al., 2001), and the preference of the target fish species for flow scheme is evaluated based on the Habitat Suitability Index (HSI), which can be determined according to the number of fish population at the target point. The maximum value of HSI is set to 1.0, and the rest of HSI values depend on the relative ratio to the maximum value. Li et al. (2011a) proposed a new habitat method for calculating ecological flow, which took into account habitat suitability and fragment, seasonal water environment factors and life stages of fish. The life stages of *S. chongi* include three phases, namely spawning period, feeding period and overwintering period. Specifically, the spawning period is from April to July, with water temperature varying from 12 °C to 18 °C. The overwintering period is from November to December and January to February.

3.4. Scenarios

One real and three hypothetical scenarios are used to assess the individual and combined effects of cascade dams and climate change, as shown in Table 2. Scenario 1 and 3 represent the historical and future unregulated natural condition, while Scenario 2 and 4 represent the historical and future regulated condition, respectively.

4. Results

4.1. Changes in temperature and precipitation

4.1.1. Evaluation of BCSD downscaling performance

The projections of future temperature and precipitation were bias corrected and spatially downscaled by the BCSD method, and the

Table 2
Scenarios used in this research.

Scenario	Research period	Cascade reservoir development
1 (baseline)	Historical	Unregulated
2	Historical	Regulated
3	Future	Unregulated
4	Future	Regulated

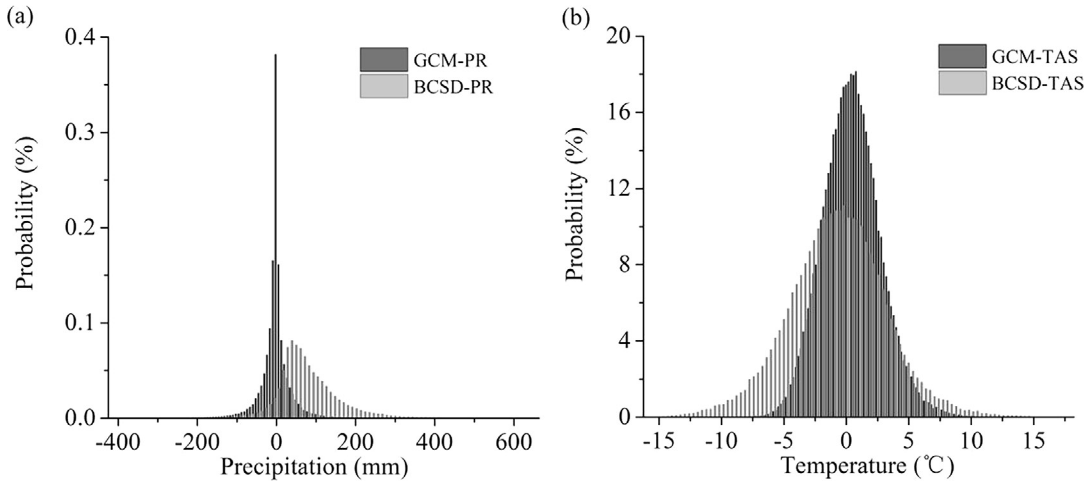

Fig. 2. The comparison of the bias probability distribution between historical BCC-CSM1-1 and BCSD downscaled (a) precipitation and (b) temperature of the Yalong River basin.

downscaling performance was evaluated by comparing downscaled GCM simulations with observations. To calculate the bias, GCM simulations and observations were converted into the same spatial resolution of 0.5° * 0.5°. Fig. 2 shows the comparison of the bias probability distribution between historical BCC-CSM1-1 and BCSD downscaled precipitation and temperature in the Yalong River basin. Clearly, BCSD can significantly improve the BCC-CSM1-1 simulated temperature and precipitation. The mean bias in temperature is −0.75 °C before BCSD downscaling and 0.46 °C after downscaling. With larger uncertainty, the mean bias in precipitation is about 76.1 mm, but a remarkable reduction to −1.5 mm is detected after BCSD downscaling.

4.1.2. Changes in future temperature

The mean annual temperature of the Yalong River basin in 1957–2012 is 3.81 °C, while that in 2020–2010 under RCP2.6, RCP4.5 and RCP8.5 is increased by about 1.63–3.25 °C at a rate of 0.016–0.487 °C/10a. There is a significant positive relationship between temperature and radiation intensity, indicating that temperature is sensitive to changes in radiation intensity. The Yalong River basin has four distinctive seasons with a higher temperature of about 11 °C from May to September. Fig. 3 clearly shows that the pattern of mean monthly temperature in 2020–2100 is similar to that in 1957–2012. The mean monthly temperature under RCP2.6, RCP4.5 and RCP8.5 is increased by about 1.2–3.9 °C compared with that in 1957–2012, and the difference in mean monthly temperature between RCP2.6 and RCP8.5 scenarios can reach a maximum of about 1.9 °C.

4.1.3. Changes in future precipitation

The mean annual precipitation of the Yalong River basin in 1957–2012 is 672.78 mm, while that in 2020–2010 under RCP2.6, RCP4.5 and RCP8.5 is increased by about 0.66–3.34% at a rate of 4.55–10.13 mm/10a. Fig. 4 shows a clear seasonal variation of the mean monthly precipitation of the Yalong River basin. In 1957–2012, precipitation occurred mainly from May to October (especially from July to September), accounting for 91.1% of the annual precipitation. In 2020–2100, there is no change in the dry and flood seasons, and 73.9–74.6% of precipitation occurs from June to September under the three climate scenarios. However, the mean monthly precipitation is not sensitive to radiation intensity, and thus it remains almost the same under the three climate scenarios.

4.2. Hydrological and fish habitat simulation

4.2.1. Fish habitat simulation

The fish habitat model developed by Li et al. (2011a) is used to describe changes in habitat quality with discharge of the Yalong River. *S. chongi*, one of the dominant fish species and a commercially important cold water fish in the Yalong River, is selected as the target fish

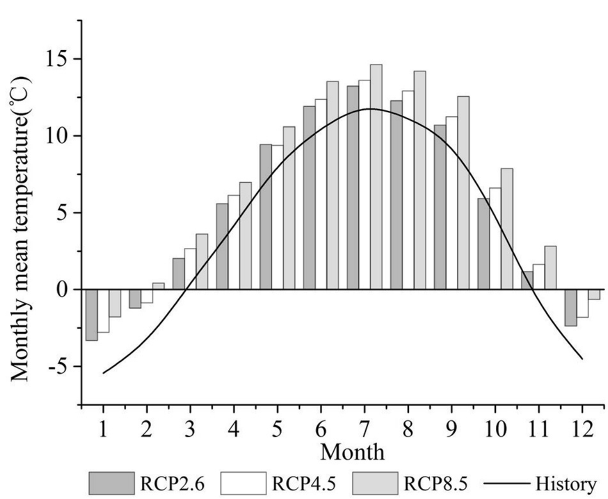

Fig. 3. The historical and future mean monthly temperature of the Yalong River basin.

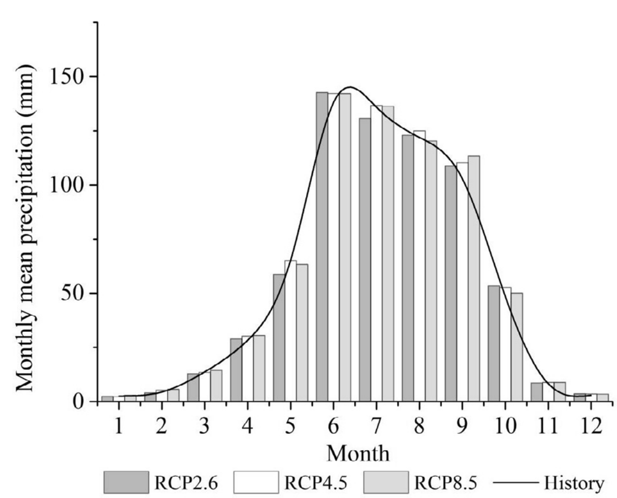

Fig. 4. The historical and future mean monthly precipitation of the Yalong River basin.

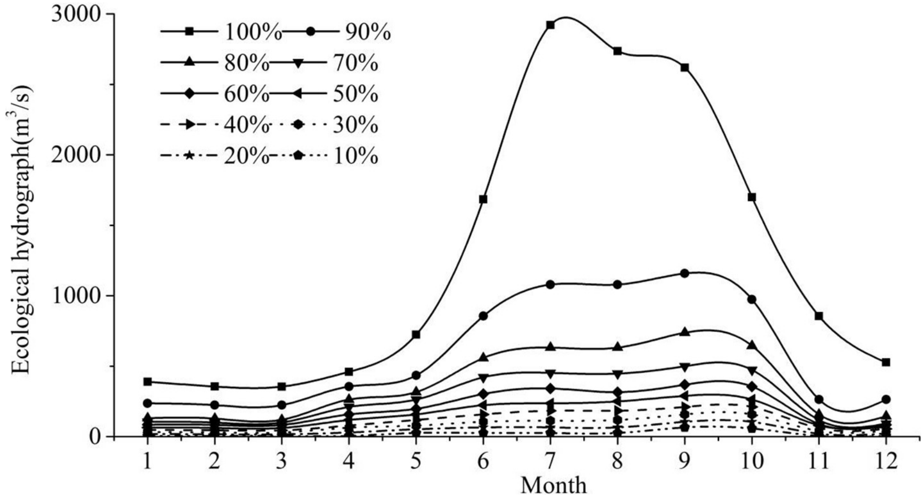

Fig. 5. Ecological hydrographs under different conservation targets of *S. chongi*. (Li et al. (2011a,b)).

species. Its spawning grounds are mostly distributed in the dewatered river channel between Jinping cascade dams in the lower reaches of the Yalong River (Fig. 1). Fig. 5 shows the ecological hydrographs for different conservation levels of *S. chongi*, and each hydrograph stands for the ecological flow required by the corresponding habitat conservation level of *S. chongi*.

4.2.2. Hydrological simulation results

The SWAT model was calibrated on a monthly scale for the period 1957–1990 and validated for the period 1991–2012, and the modeling performance was evaluated by comparing SWAT simulated inflow against the observed inflow. The natural inflow and discharge of cascade reservoirs were simulated according to the operation policy. As shown in Fig. 6 and Table 3, there is a significant correlation between observed and simulated runoff with a $R^2 > 0.75$ and a $NSE > 0.75$. After removing the seasonal cycle, R^2 and NSE indicate a slight decrease, but are still larger than 0.60 for both middle and lower river reaches. The simulated and observed mean monthly runoff in the middle reaches of the Yalong River basin are 640.26 and 667.10 m^3/s; while that in the lower reaches are 1218.07 and 1209.44 m^3/s, respectively.

4.3. Prediction of runoff and fish habitat quality

4.3.1. Hydrological prediction

The downscaled climate projections of BCC-CSM1-1 were used to drive the calibrated SWAT hydrological model to predict runoff responses to changes in future climate of the Yalong River basin. The runoff of the Yalong River is derived mainly from precipitation, and thus changes in runoff are consistent with the seasonal changes in precipitation. In this study, changes in future runoff in the middle and lower reaches of the basin are predicted. However, as changes in annual runoff of the JinpingI Reservoir (an annual regulation reservoir) and Lianghekou Reservoir (a multi-year regulation reservoir) are determined primarily by natural precipitation but less by cascade dam construction, we analyze changes in future runoff under no construction of cascade dams, as shown in Fig. 7. It shows that in 1957–2012, the mean annual runoff is 667.10 m^3/s and 1209.44 m^3/s in the middle and lower reaches, respectively. However, in 2020–2100, there is a frequent alternation between wet and dry years, resulting in a large variation of runoff but with an overall increasing trend, which is particularly pronounced under RCP4.5. The mean annual runoff is 745.64–778.02 m^3/s and 1379.05–1439.42 m^3/s in the middle and lower reaches, with an increase of 11.77–16.63% and 14.02–19.02% compared with that in the historical reference period, respectively. Under RCP2.6, the mean annual runoff remains largely stable over time, and that of the middle reaches is increased linearly at first at a rate of -1.95 m^3/s per decade before 2035, after which it remains largely stable. Under RCP4.5, the mean annual runoff is significantly increased at a rate of 16.80 and 29.22 m^3/s per decade in the middle and lower reaches, respectively. Under RCP8.5, the mean annual runoff is increased at a rate of 2.01 and 12.22 m^3/s per decade in the middle and lower reaches, respectively. In summary, the runoff is increased more significantly in the lower reaches than in the middle reaches.

Fig. 8 shows a nonuniform intra-annual distribution of runoff in the Yalong River basin, where the flood season is from June to October and the major flood season is from July to September. The natural runoff of the middle and lower reaches in the flood season accounts for 75.76% and 76.21% of the total annual runoff before reservoir regulation, but 51.94% and 53.53% after reservoir regulation, respectively. In 2020–2100, the difference in natural runoff between flood and non-flood seasons is expected to increase, resulting in high and concentrated runoff in the flood season but low and uniform runoff in the non-flood season. The coefficient of Variation (Cv) is defined as the ratio of the standard deviation to the mean. Here, it is utilized to show the extent of variability in relation to the mean value. Under no reservoir regulation, Cv of the runoff is 0.84 and 0.77 in the middle and lower reaches, and the natural runoff in the flood season is 1396.12–1464.48 m^3/s and 2476.08–2600.84 m^3/s, with an increase of 15.10–20.74% and 11.94–17.58% compared with that in the historical flood season, respectively. However, the mean runoff in the major flood season from July to September is increased more significantly by 16.33–23.23% and 9.47–15.45%, respectively. The runoff of the middle and lower reaches in the flood season accounts for 78.02–78.44% and 74.82–75.29% of the annual runoff, with an increase of 2.26–2.68% and $-1.39 \sim -0.92$% compared with that in the history, respectively. However, the runoff in the non-flood season accounts for 21.56–21.98% and 24.71–25.18% of the annual runoff, with a reduction of 2.26–2.68% and $-1.39\% \sim -0.92\%$, respectively.

The construction of cascade reservoirs can contribute to reducing the intra-annual difference in runoff with a Cv of 0.39 and 0.40 in the middle and lower reaches, as shown in Fig. 8. The runoff of the middle reaches is controlled mainly by the Lianghekou Reservoir. Under cascade dam construction, the future mean runoff in the flood season is 957.74–1036.10 m^3/s, with a decrease of 29.25–31.40% compared with future natural runoff; and the runoff in the flood season accounts for 53.54–55.47%, with a decrease of 22.97–24.48%. However, the runoff of the lower reaches is controlled mainly by the Jinping I Reservoir, and cascade dam construction can result in a decrease in the difference in runoff between flood and non-flood seasons. Under cascade dam

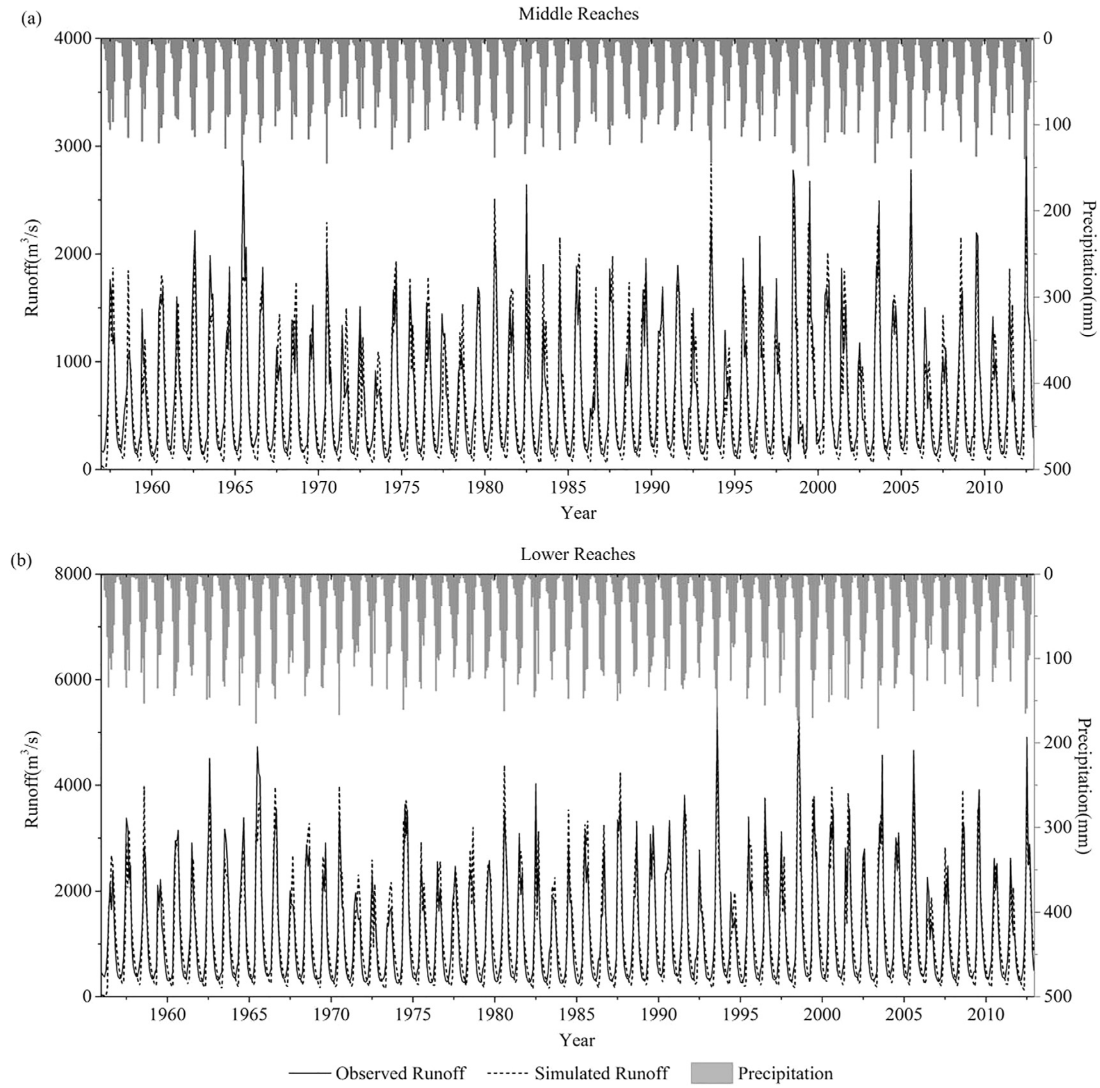

Fig. 6. The simulated and observed inflow of (a) the middle and (b) lower reaches of the Yalong River basin during 1957–2012.

Table 3
The performance of the SWAT model in hydrological simulation.

Basin	with seasonal cycle				without seasonal cycle			
	Calibration		Validation		Calibration		Validation	
	R^2	*NSE*	R^2	*NSE*	R^2	*NSE*	R^2	*NSE*
Middle reach	0.78	0.76	0.80	0.79	0.73	0.68	0.70	0.63
Lower reach	0.85	0.84	0.87	0.87	0.77	0.78	0.69	0.66

construction, the future mean runoff in the flood season is 1877.69–1950.84 m^3/s, with a decrease of 23.78–25.52% compared with future natural runoff; and the runoff in the flood season accounts for 55.74–56.50%, with a decrease of 18.79–19.38%.

4.3.2. *Prediction of fish habitat sustainability*

Fig. 9 shows changes in future annual ecological conservation degree before and after cascade dam construction. Under no cascade dams, the future mean annual ecological guarantee rate of the Yalong River basin varies slightly between 93.94% and 94.72%. JinpingI Reservoir as an annual regulation reservoir can increase the runoff in dry periods from December to April of the next year and impound water in the flood season. As a result, the ecological water requirement of *S. chongi* in their spawning period can be well satisfied and the possible impact of large discharge in the flood season on the fish habitat can be avoided. Thus, the habitat quality of the Yalong River basin is significantly improved with an ecological conservation degree of 97.03–97.16% after cascade dam construction.

Fig. 10 shows the monthly ecological conservation degree of the Yalong River basin in the future. Under unregulated conditions, the monthly ecological conservation degree of the Yalong River basin is maintained at a high level of > 95% from September to March, but a lower level of 70–80% from April to May during which *S. chongi* spawn. Worse still, there is low natural runoff from April to May, making it difficult to meet the ecological water requirement for the spawning of *S. chongi*. However, the runoff of the lower reaches from April to May can be greatly improved after reservoir regulation, resulting in a significant improvement of the ecological conservation degree and consequently improvement of the habitat quality for the spawning of *S. chongi*. The impoundment of water from June to September can reduce the discharge to the middle and lower reaches, resulting in a 3.5% decrease of the ecological conservation degree. In summary, the habitat quality is improved by about 2% after reservoir regulation.

5. Discussion

The relative change rate, which is defined as the ratio of changes in

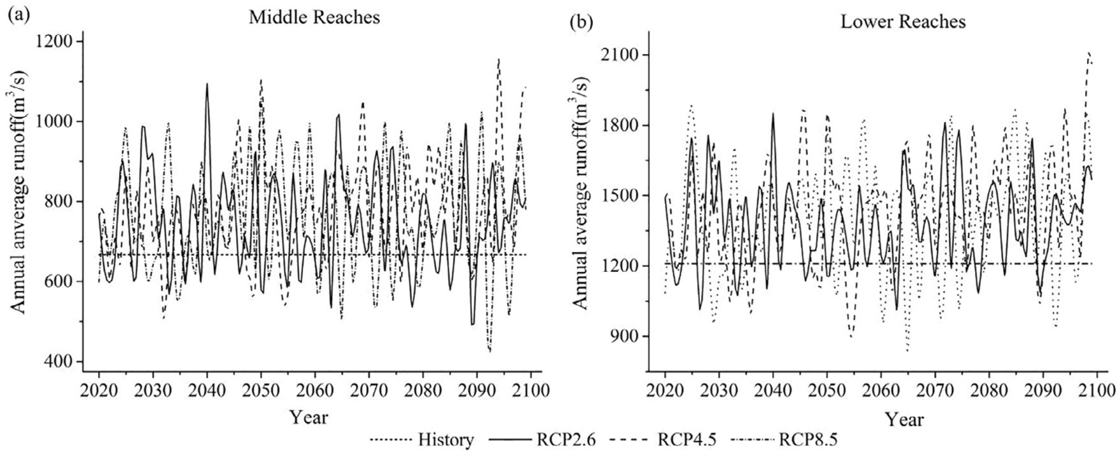

Fig. 7. The time series of predicted mean annual inflow (m^3/s) in the (a) middle and (b) lower reaches from 2020 to 2100 under RCP2.6, RCP4.5 and RCP8.5, respectively.

the outcome variable with and without the influence factor to the standard deviation of the outcome variable under natural conditions, is used in this study to evaluate the individual and combined effects of cascade dam construction and climate change on the runoff and fish habitat quality of the Yalong River basin. Accordingly, the relative change rate of runoff attributed to cascade dam construction (α_1) is defined as the ratio of the change in runoff before and after cascade dam construction to the standard deviation of natural runoff; that attributed to climate change (α_2) is defined as the ratio of the change in runoff in 2020–2100 relative to that in 1957–2012 to the standard deviation of natural runoff in 1957–2012 under no cascade dams; while that attributed to the combined effect (α_3) is defined as the ratio of the change in runoff in 2020–2100 relative to that in 1957–2012 to the standard deviation of natural runoff in 1957–2012 under cascade dam construction, respectively. Similarly, the relative change rate of habitat quality attributed to cascade dam construction (α_4) is defined as the ratio of the change in ecological conservation degree before and after cascade dam construction to the standard deviation under natural conditions; that attributed to climate changes (α_5) is defined as the ratio of the change in ecological conservation degree in 2020–2100 relative to that in 1957–2012 under no cascade dams to the standard deviation under natural conditions; while that attributed to the combined effect (α_6) is defined as the ratio of the change in ecological conservation degree in 2020–2100 relative to that in 1957–2012 under cascade dam

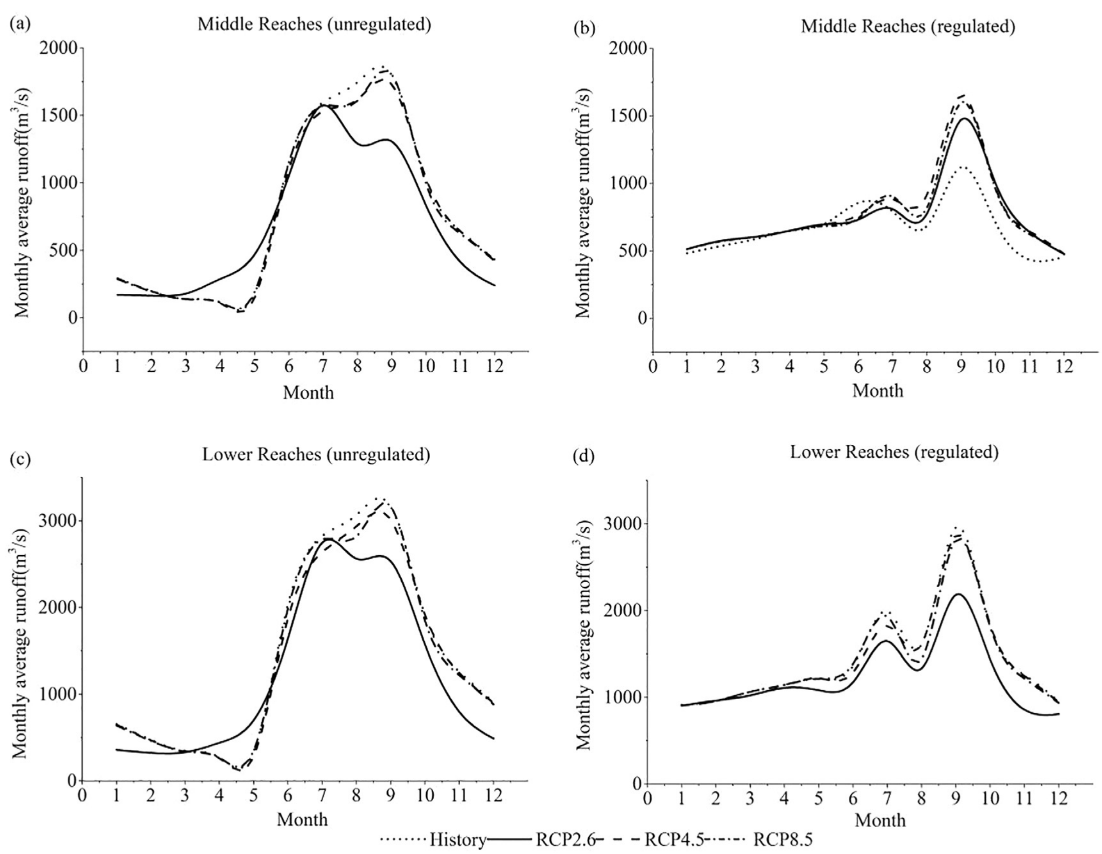

Fig. 8. Mean monthly runoff (m^3/s) of the Yalong River basin from 2020 to 2100 under RCPs 2.6, 4.5 and 8.5, respectively. The middle reaches under (a) unregulated and (b) regulated conditions; and the lower reaches under (c) unregulated and (d) regulated conditions.

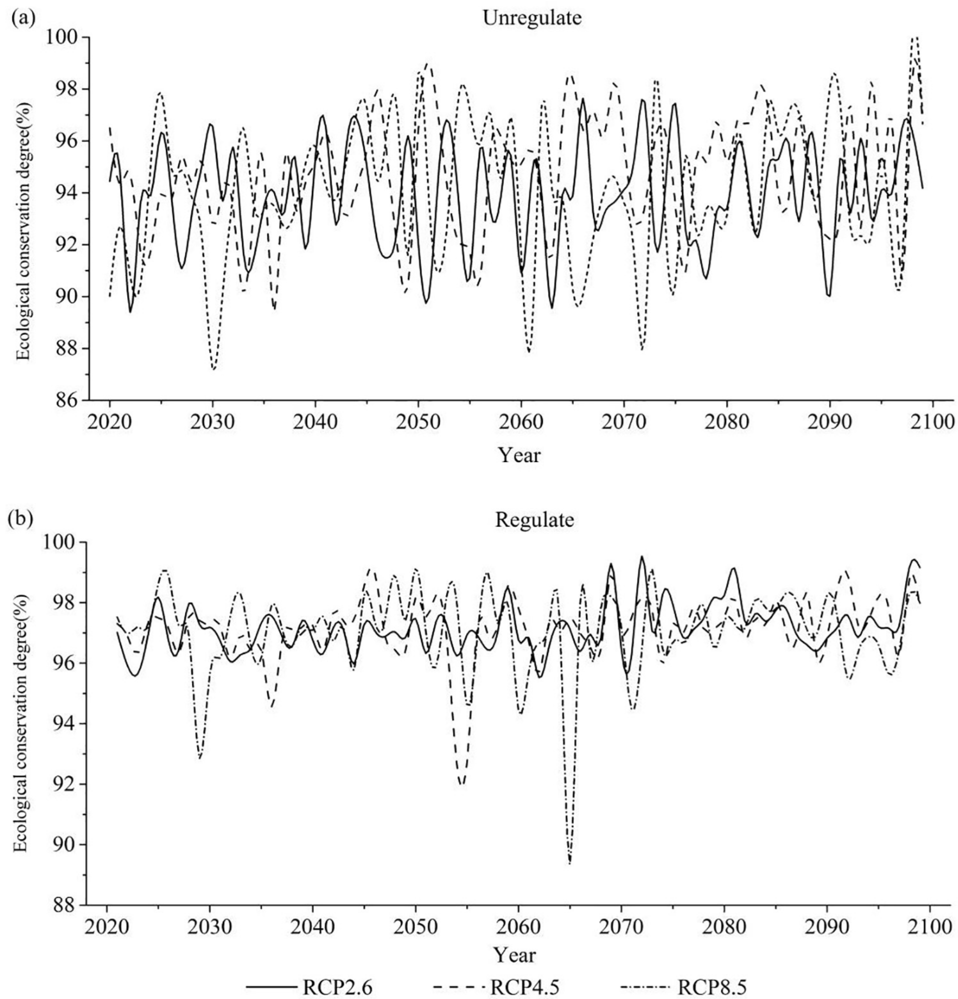

Fig. 9. Future annual ecological conservation degree (%) of the Yalong River basin from 2020 to 2100 under RCPs 2.6, 4.5 and 8.5, respectively. (a) unregulated condition; (b) regulated condition.

construction to the standard deviation under natural conditions, respectively.

$$\alpha_{i,j} = \left|\frac{d_j}{D_j}\right|,\ i = 1, 2, \cdots, 6;\ j = 1, 2, 3, \cdots, 12 \tag{7}$$

$$D_j = \sqrt{\frac{\sum_{m=1}^{n} (X_{jm} - \bar{X_j})^2}{n-1}},\ j = 1, 2, 3, \cdots, 12 \tag{8}$$

$$d_j = \bar{X_j} - \bar{x_j},\ j = 1, 2, 3, \cdots, 12 \tag{9}$$

where α_{ij} is the relative change rate of the mean monthly runoff or ecological conservation degree of the j^{th} month; $D_j$is the standard deviation of the mean monthly runoff or ecological conservation degree of the j^{th} month; d_j is the difference in mean annual flow rate or ecological conservation degree of the j^{th} month under cascade dam construction or climate change; X_{jm} and $\bar{X_j}$ are the mean monthly or annual runoff or the ecological conservation degree in different years before cascade dam construction or climate change; n is the number of years; and $\bar{x_j}$ is the mean annual runoff and ecological conservation degree after cascade dam construction or climate change, respectively.

The effects of cascade dam construction and climate change on the runoff of the Yalong River basin are shown in Fig. 11. The construction of cascade dams results in a significant change in runoff, and the relative change rate of the middle reaches from January to May is much larger than that in other months. This is because the natural runoff is low from January to May and, consequently, the discharge of the reservoir is 2.3–2.4 times the usual discharge. However, the runoff in the flood season is less affected by reservoir regulation, resulting in a relatively lower relative change rate. In general, the relative change rate under RCP2.6 is slightly higher than that under RCP4.5 and RCP8.5. Under cascade dam construction, the mean monthly runoff under RCP4.5 and RCP8.5 changes slightly, but shows an increasing trend with the increase of greenhouse gases. The reservoir can significantly regulate the runoff of the lower reaches, especially in the dry season, resulting in a larger relative change rate from January to May.

Under the effect of climate change, the natural runoff is high in the flood season from June to October, and it is less affected by climate change and thus has a lower relative change rate compared with that in the non-flood season. The future natural runoff of the middle reaches in the dry February and March is changed by 45 and 20 m^3/s compared with the historical natural runoff, resulting in a low relative change rate. It is noted that the relative change rates are similar across different RCP scenarios. However, the runoff under RCP2.6, RCP4.5 and RCP8.5 show an increasing trend compared with historical runoff, resulting in an increase of the relative change rate over time. Thus, it can be concluded that climate change has an increasingly significant effect on runoff. However, climate change generally has a lower effect on runoff than cascade dam construction, with a relative change rate of lower than 4.

Under the effects of combined climate change and cascade dam construction, the relative change rate pattern of runoff is similar to that

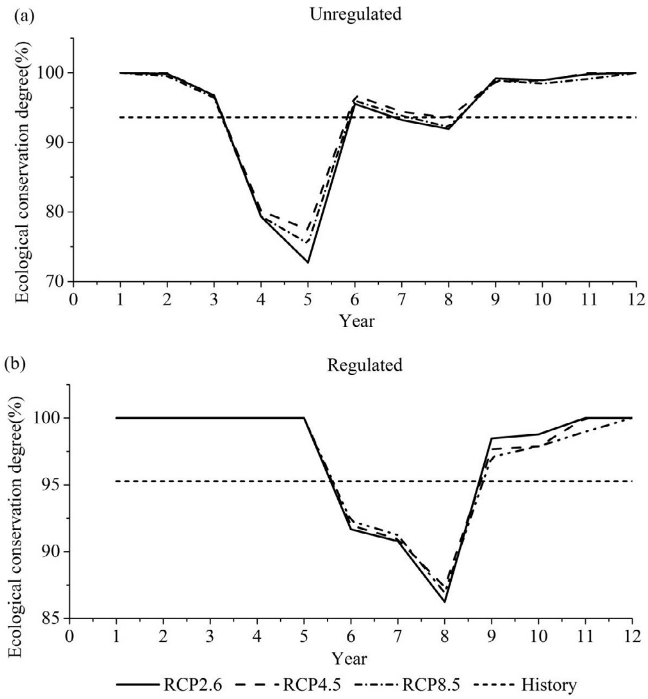

Fig. 10. Monthly ecological conservation degree (%) of the Yalong River basin from 2020 to 2100 under RCPs 2.6, 4.5 and 8.5, respectively. (a) unregulated condition; (b) regulated condition.

under the effects of only cascade dam construction, in which the relative change rate increases from November to March of the next year, and it is higher than that from April to May and from June to October (about 1). Specifically, the relative change rate of the runoff of the middle reaches from February to May is slightly lower than that under only cascade dam construction, with a maximum of 78%; but it is slightly increased from November to January compared with that under only cascade dam construction but close to that under only climate change. Thus, changes in runoff from February to May are more affected by cascade reservoirs, whereas that from November to January are more affected by climate change.

For the lower reaches, the relative change rate of runoff under combined climate change and cascade dam construction is also similar to that under only cascade dam construction, but it is generally higher than that of the middle reaches. In general, the cascade reservoirs have a large impact on the runoff of the lower reaches, especially in the non-flood season from January to May, with a relative change rate similar to that under only cascade dam construction. The runoff is large in the flood season from June to October, with a large mean standard deviation and thus a low relative change rate. However, the relative change rate of runoff in the non-flood period from November to December low and dominantly affected by climate change.

The effects of cascade dam construction and climate change on fish habitat quality of the Yalong River basin are shown in Fig. 12. Under the effects of cascade dam construction, the relative change rate is high from April to May, especially under RCP2.6; whereas that in other months is about 1, indicating that cascade dam construction has a more significant effect on fish habitat quality from April to May. The construction of cascade dams enables JinpingI Reservoir to discharge more water from April to May, which is helpful for spawning of *S. chongi* and improving the ecological guarantee rate. However, the monthly natural runoff in dry periods from November to January is slightly increased, resulting in an improvement of the fish habitat quality and a higher ecological conservation degree. Thus, it can be concluded that cascade dam construction causes no damage to fish habitat with a relative change rate of approximately 0.

Under the effects of climate change, the relative change rate of the ecological conservation degree is higher in April and May but lower than 1.5 in other months, indicating that climate change can have a more significant effect on the habitat quality in the non-flood periods than in the flood periods.

Under the effects of combined climate change and cascade dam construction, the relative change rate of the ecological conservation degree is maintained at a stable level of 1. Despite their significant individual effects, the combination of climate change and cascade dam construction has small effects on fish habitat quality, especially in April and May. Climate change has a persistent and large effect on the fish habitat quality. The ecological requirement is considered in the operation of cascade reservoirs, which has no damage on fish habitat quality but can improve the ecological conservation degree in dry periods.

6. Conclusions

In this study, we investigated future changes in runoff and fish habitat quality of the Yalong River basin attributed to the individual and combined effects of construction of cascade dams and climate change. The main conclusions are summarized as follows:

(1). The mean annual temperature of the Yalong River basin in 2020–2100 is increased by about 1.63–3.25 °C at a rate of 0.016–0.487 °C/10a compared with that in 1957–2012; while the mean annual precipitation is increased by about 0.66–3.34% at a rate of 4.55–10.13 mm/10a. There is no change in the dry and flood seasons, but the difference in precipitation between dry and wet periods is increased. There is a significant positive relationship between temperature and radiation intensity, and thus temperature is sensitive to changes in radiation intensity.

(2). The SWAT model is shown to have high hydrological simulation performance with a $R^2 > 0.75$ and a $NSE > 0.75$ for both calibration and validation. In 2020–2100, the annual runoff shows an increasing trend, especially under RCP4.5. The mean annual runoff of the middle and lower reaches of the Yalong River in 2020–2100 are increased by 11.77–16.63% and 14.02–19.02% in comparison with those in 1957–2012, respectively. The natural runoff in the flood season is 1396.12–1464.48 m^3/s and 2476.08–2600.84 m^3/s in the middle and lower reaches, with an increase of 15.10–20.74% and 11.94–17.58% compared with that in the history, respectively. However, the construction of cascade dams results in 22.97–24.48% and 18.79–19.38% decrease in the runoff of the middle and lower reaches in the flood season compared with that under no cascade dams, respectively.

(3). The habitat quality of the Yalong River basin is significantly improved by 2% with an ecological conservation degree of 97.03–97.16% after cascade dam construction.

(4). The construction of cascade dams results in a significant change in runoff, and the relative change rate of the middle reaches from January to May is much larger than that in other months. However, climate change generally has a lower effect on runoff than cascade dam construction, with a relative change rate of lower than 4. Under the combined effects of climate change and cascade dam construction, the runoff of the middle reaches from February to October is more affected by cascade reservoirs, whereas that from November to January are more affected by climate change. Similarly, cascade dam construction has a more significant effect on runoff of the lower reaches than climate change except in November and December.

(5). Cascade dam construction has a significant effect on fish habitat quality from April to May; while climate change has a high effect in the dry season but a low effect in the flood season. Despite their significant individual effects, the combination of climate change and cascade dam construction has small effects on fish habitat

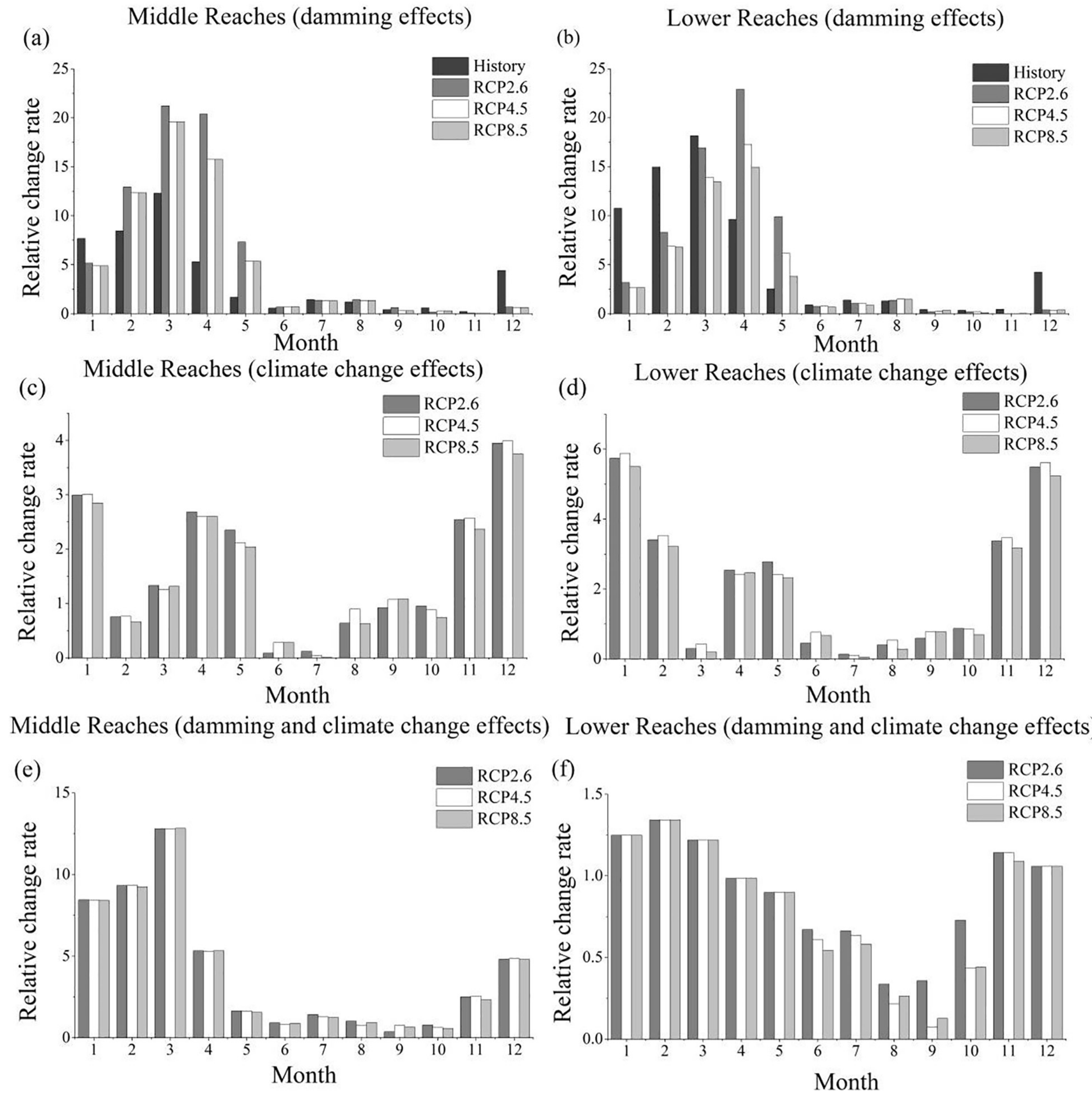

Fig. 11. Monthly relative change rate of runoff of the Yalong River basin. The effect of damning on (a) the middle and (b) lower reaches; the effect of climate change on (c) the middle and (d) lower reaches; and the combined effect on (e) the middle and (f) lower reaches.

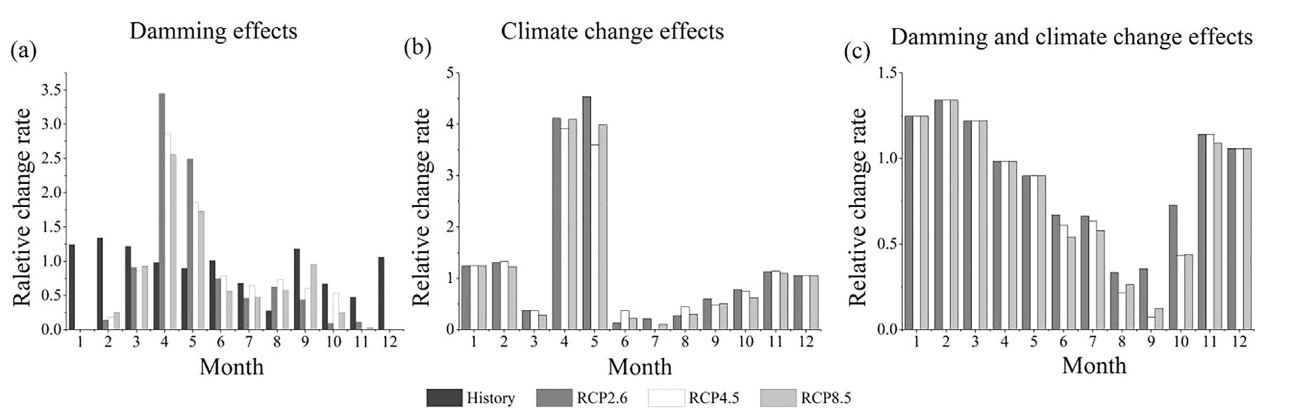

Fig. 12. The relative change rate of monthly ecological conservation degree of the Yalong River basin. (a) damming effect; (b) climate change effect; and (c) combined effect.

quality. The reservoir causes no damage on fish habitat quality, but rather it can significantly improve the ecological conservation degree in dry periods.

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